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13. ABSTRACT (Maximum 200 words) Temporary broadband networks are clearly an advantage to efforts to calibrate relatively unknown regions. Our results demonstrate the type of information that can be determined with this type of data. The combination of broadband, digital three-component array data and state-of-the-art multidimensional digital signal processing algorithms have provided considerable insight into both the composition of the regional wavefield and the nature of lithospheric heterogeneities. Our Lg results have clarified a long-standing debate about the cause of Lg blockage by the Tibetan Plateau. Understanding the nature of this blockage is critical to understanding the effect it has on common discriminants that utilize Lg. Continuing regional waveform modeling has led to a better understanding of north-south variations in mantle structure and the effects these variations have on regional waveforms. We have also been able to better quantify the effect of event mislocation on derived layered velocity models in the Tibetan Plateau. Studies of teleseismic shear-coupled P-waves have revealed a zone of partial melting in the northern Tibetan Plateau that is closely related to the anomalous upper mantle structure in the region. We have completed the determination of a local magnitude scale for events recorded by the 1991-92 Tibetan Plateau seismic experiment. This analysis suggests that there is a distance bias that underestimates magnitudes for station-event separations of more than 600km. This may be related to the increased attenuation of Lg at similar distances that we observed in our Lg analysis. Much of this work has been published in journals, meeting abstracts, and symposium volumes.			
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**Contract #F49620-94-1-0066DEF**

**THE APPLICATION OF BROADBAND ARRAYS AND NETWORKS TO  
SEISMIC MONITORING OF UNCALIBRATED REGIONS**

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**Prepared for:**

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## **RESEARCH OBJECTIVES**

One approach to calibrating areas of nonproliferation concerns is the use of mobile arrays of new generation, high dynamic range, broadband digital seismic instruments. This project uses existing data from a variety of seismic deployments to assess the utility of this approach and to develop strategies for using temporary deployments to gather data to address seismic monitoring concerns. We will use data from deployments in Turkmenistan, Kyrgyzia, and the Tibetan Plateau that span a wide range of scales with minimum station spacings of 0.150 to 100 km over array dimensions of 2 to 1500 km.

The broad areas of research are: I) Characterization of lithospheric heterogeneities through analysis of broadband array data; II) Regional source and structure studies using closely spaced broadband stations; and III) Detection, location, and discrimination studies to evaluate both the utility of temporary deployments and build background observations for Central Asia and the Middle East. The application of the methods we propose to a variety of data sets allows us to both characterize multiple regions and assess the portability of these methods.

## **STATEMENT OF WORK**

### **Task I - Characterization of Lithospheric Heterogeneities**

- Characterize lithospheric heterogeneity and determine their effect on broadband waveforms using the Tibet, Alibek and PFO dense arrays.

### **Task II - Regional Source and Structure Studies**

- Evaluation of combined source and structure modeling approaches using the Tibetan Plateau dataset.
- Application of preferred methodology to source and structure studies using regional events recorded by Alibek, KNET, and Tibet stations.
- Assessment of the affects of complex structure on regional waveforms using Tibet, CDSN, and KNET data.

### **Task III - Detection, Location, and Discrimination in Uncalibrated Regions**

- Regional broadband 3-component dense array detection and discrimination studies using Alibek and PFO data.
- Compilation of common seismic discriminant measurements for Central Asia and Middle East seismicity using data recorded by Alibek, KNET, and Tibet stations.

## SUMMARY OF EFFORT

Temporary broadband networks are clearly an advantage to efforts to calibrate relatively unknown regions. Our results demonstrate the type of information that can be determined with this type of data. The combination of broadband, digital three-component array data and state-of-the-art multidimensional digital signal processing algorithms have provided considerable insight into both the composition of the regional wavefield and the nature of lithospheric heterogeneities. Our Lg results have clarified a long-standing debate about the cause of Lg blockage by the Tibetan Plateau. Understanding the nature of this blockage is critical to understanding the effect it has on common discriminants that utilize Lg. Continuing regional waveform modeling has led to a better understanding of north-south variations in mantle structure and the effects these variations have on regional waveforms. We have also been able to better quantify the effect of event mislocation on derived layered velocity models in the Tibetan Plateau. Studies of teleseismic shear-coupled P-waves have revealed a zone of partial melting in the northern Tibetan Plateau that is closely related to the anomalous upper mantle structure in the region. We have completed the determination of a local magnitude scale for events recorded by the 1991-92 Tibetan Plateau seismic experiment. This analysis suggests that there is a distance bias that underestimates magnitudes for station-event separations of more than 600km. This may be related to the increased attenuation of Lg at similar distances that we observed in our Lg analysis. Much of this work has been published in journals, meeting abstracts, and symposium volumes.

## ACCOMPLISHMENTS

### TASK I -- Characterization of Lithospheric Heterogeneity

Our regional waveform modeling has demonstrated the effects that a rapid variation in lithospheric properties can have on regional P and S waveforms. Over a distance range of only 150 km, we observe rapid broadening of S-waveforms as they cross from the southern Tibetan Plateau into the northern Tibetan Plateau. This rapid transition is responsible for the well-known absence of high-frequency Sn propagation in the northern plateau. We now know that long-period S-waves do propagate within the northern plateau and that the loss of high-frequency occurs very rapidly when waves cross the northern plateau.

Our analysis of shear-coupled P-waves from teleseismic sources has demonstrated the utility of using these phases to characterize average crustal structure. Using data recorded in the Tibetan Plateau, we documented a change in crustal structure that is closely related to changes in upper mantle structure. These heterogeneities had long been hypothesized to exist due to changes in upper mantle structure. However, our study is the first to clearly document 15-20km of crustal thinning in the northern Tibetan Plateau. This documentation was possible due to the use of shear-coupled P-waves that average the crustal structure within 100-300 km of a recording station, thus allowing us to examine lateral changes in structure on a scale not possible with long-period surface waves.

We have developed a statistical array processing algorithm for three-component seismic array data. Our analysis of regional array data using this novel processing scheme shows that the P and S codas, and the Lg wavetrains associated with regional events (observed at Pinon Flat Observatory, southern California) consist of considerable amounts of forward scattered/multipathed energy. It is only with the arrival of surface waves (apparent velocity approximately 3 km/s) that the coda is dominated by a coda that is "random" in nature. The fact that much of this later coda cannot be modeled as plane waves suggests that it is not scattered from distant sources; this premise is consistent with small aperture array observations for local sources which suggest that much of the "random" coda results from very localized site effects. Numerical simulations of teleseismic wave propagation suggest a correlation between the coda level and rate of decay and the aspect ratio of lithospheric heterogeneities. For the teleseismic case, the heterogeneity aspect ratio appears to play an important role in determining the coda level and rate of decay by controlling the extent to which vertically propagating energy is scattered into the horizontal direction. These teleseismic modeling results provided the motivation for numerical simulations of regional wave propagation using models containing spatially anisotropic heterogeneities. Our modeling results suggest that for the regional case, the heterogeneity aspect ratio plays an important role in determining the extent to which energy is forward scattered and, consequently, trapped in the crustal waveguide.

The spatially isotropic, homogeneously and randomly distributed lithospheric heterogeneity model popular for nearly three decades is inconsistent with three-component array observations. This is a very important finding in that the detailed structure of the crustal waveguide plays a crucial role in shaping the regional wavefield. The nature of lithospheric heterogeneities, therefore, has important implications for the generation and propagation of regional phases used in monitoring, such as Lg, and for the types earth models used in waveform modeling for source and structure parameters.

The single/multiple scattering (S/MS) theory for coda generation was invoked nearly thirty years ago to explain the apparent random nature of seismic coda observed at sparse, short-period networks. The most basic assumptions in modeling seismic coda using the S/MS model are: (i) scattering sources

are distributed randomly and homogeneously in space, (ii) scattering source have isotropic radiation patterns, and (iii) single/multiple body-wave to body-wave scattering, predominantly S wave.

The nature of seismic coda revealed by three-component array observations is in almost complete disagreement with S/MS model for coda generation. Array observations show that both P and S coda do not exhibit the random behavior indicative of generation by isotropic scattering from randomly distributed heterogeneities, but is composed predominantly forward scattered body wave energy. This implies that scattering sources cannot be both distributed randomly in space AND have isotropic radiation patterns. Our analysis shows that scattering sources are confined to a fairly limited volume sub-parallel to the direct arrivals, and/or that scattering radiation patterns have predominantly forward lobes. The scattered wavefield observed at three-component arrays takes on a more random character only with the arrival of the surface waves. The most prominent feature of regional surface wave coda is, however, not its random nature but considerable multi-pathing. The random component of the surface wave coda is composed predominantly of surface wave energy (which explains its slow decay rate) that appears to be closely coupled to very local structure (which explains the coda's apparent random behavior when compared across a sparse network of sensors).

The most important finding of our scattering research is that heterogeneities in lithospheric structure should not be modeled as homogeneously and randomly distributed, isotropic scattering sources. Results from analysis of local, regional and teleseismic data suggests that lithospheric heterogeneities are spatially anisotropic. None of the array observations, which provide a very different sampling of the wavefield than that provided by isolated sensors, are consistent with the S/MS model for coda generation. Our research suggests that the random nature of the coda is not a real characteristic, but due only to the fact that observations furnished by sparse networks provide a random and spatially aliased sampling of the wavefield, thereby effectively annihilating our ability to resolve the true nature of the scattered wavefield. The spatially anisotropic heterogeneity model suggested by our analysis not only allow us to more accurately model the observations, but also provides for intuitively appealing models consistent with geological models where layers do not have infinite lateral extent, but are truncated by faulting, folding, and pinch outs.

Three-component array data provides a previously unavailable sampling of the elastic wavefield. The abundance of information provided by three-component array data allows us to fully address the most fundamental questions about high-frequency elastic wave propagation which cannot be resolved using data from a single component array, or a sparse network of three-component sensors.

## **TASK II - Regional Source and Structure Studies**

Source mechanisms for 38 events located on the Tibetan Plateau have been estimated using time domain inversion of long period displacement seismograms from data collected by the 1991-92 PASSCAL Tibetan Plateau deployment (Randall et al, 1995). We were able to constrain the depth of the events from the waveform inversion, and demonstrate that the results are only weakly dependent on the velocity model for the cases we used. We observed Mb:Mo anomalies in a region that has historically been recognized as a source of events that have anomalous Mb:Ms ratios. Furthermore, we found the mechanism was only weakly dependent on small errors in the source location for a well-constrained event. We have found that the analysis of broadband regional waveforms using simple existing velocity models derived from teleseismic surface wave tomography is an effective technique for the regional characterization of source mechanism and source depths of earthquakes. Using these robust source mechanism estimates, we will continue our regional characterization by refining the earth structure models. With more accurate earth models, we expect that we will be able

to model broader bandwidth data and look for depth phases and detailed regional propagation behavior.

The Tibetan Plateau is a dominant structural feature influencing seismic wave propagation in Central Asia. Using data from the 1991-92 Tibetan Plateau Seismic Experiment deployment of broadband PASSCAL sensors, we are studying the effects of the Tibetan Plateau on a variety of regional phases propagating within the plateau and crossing its boundaries. Examples of specific studies undertaken under this contract include a study of Lg propagation in the Tibetan Plateau (McNamara et al, 1995) and an ongoing analysis of broadband Sn propagation (Crotwell et al., 1995; Owens et al, 1995).

The propagation and attenuation characteristics of Lg are used to document that Lg can propagate within the thickened crust of the Tibetan Plateau and to confirm previous studies showing that all boundaries of the plateau are effective barriers to Lg propagation. Our results further indicate that attenuation of Lg within the plateau is relatively high, comparable to areas of active tectonics, such as the Basin and Range Province. The second study involves waveform modeling of Pn and Sn waveforms from regional events of moderate magnitude. Source mechanisms for these events have been recently published, providing the necessary constraints to begin detailed structural modeling. It has been known for a decade that there are significant lateral variations in Sn propagation within the plateau, specifically that the central northern Tibetan Plateau blocks the propagation of high-frequency Sn phases. Using broadband regional seismograms from events within the plateau, we document that this blockage is strongly frequency-dependent. The available station spacing allows us to observe a rapid loss of high frequencies as regional S phases cross into the northern plateau while frequencies below 0.05Hz propagate throughout the plateau. Variations in the displacement pulse-shapes through the transition into the northern plateau are more easily explained by a changes in Poisson's ratio with depth than by simply rapid changes in the attenuation structure.

### **TASK III -- Detection, Location, and Discrimination in Uncalibrated Regions**

In an effort to evaluate regional source discriminants for the plateau, we have developed a local magnitude scale to use in the ML:Mo discriminant. We first evaluate station-network ML residuals for 82 regional events using broadband seismograms from the 1991-92 experiment corrected to a Wood-Anderson response. Initial analysis indicates that rapid attenuation of regional Lg at distances beyond 600 km is evident in the amplitude terms and may bias magnitude estimates at these distances. We are now beginning to locate the 80-100 events recorded in the 1991-92 that are not in the PDE catalog to evaluate the detection threshold of the PDE catalog in this region.

We have developed a multivariate statistical analysis detection algorithm that can be used with single-site three-component, single component array, and three-component array data. A paper describing this technique was published (Wagner and Owens, 1996).

## PERSONNEL SUPPORTED

Principal Investigator: Thomas J. Owens

Other Post-Doctoral Investigators: George Randall  
Jeroen Ritsema  
Gregory S. Wagner

Graduate Students: H. Philip Crotwell, Ph.D. Student  
Daniel E. McNamara (no direct salary support)  
Mark Powers, MS Student  
Arleen A. Hill, MS Student

## REFEREED PUBLICATIONS

McNamara, D. E., T. J. Owens, and W. R. Walter, Propagation Characteristics of Lg Across the Tibetan Plateau, *Bull. Seism. Soc. Am.*, 85, 457-469, 1996

McNamara, D.E., W.R. Walter, T.J. Owens, and C.J. Ammon, Upper mantle velocity structure beneath the Tibetan Plateau from Pn travel time tomography, *J. Geophys. Res.* 102, 493-506, 1997.

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Wagner, G.S., Resolving diversely polarized, superimposed signals in three-component seismic array data, *Geophys. Res. Lett.*, 23, 1837-1840, 1996.

Wagner, G. S. and T. J. Owens, Signal Detection using Multi-Channel Seismic Data, *Bull. Seism. Soc. Am.*, 86, 221-231, 1996.

Wagner, G.S., Numerical simulations of wave propagation in heterogeneous wave guides with implications for regional wave propagation and the nature of lithospheric heterogeneity, *Bull. Seism. Soc. Am.*, 86, 1200-1206, 1996.

Wagner, G.S., Regional wave propagation in southern California and Nevada: Observations from a three-component seismic array, *J. Geophys. Res.* 102, 8285-8311, 1997.



## TECHNICAL REPORTS

Crotwell, H.P., M.R. Powers, T.J. Owens, and G. Zandt, Characterization of seismic structure and wave propagation within the Tibetan Plateau, *Proceedings of the 18th Annual Research Symposium on Monitoring a Comprehensive Test Ban Treaty*, Annapolis, MD, September 1996.

Owens, T.J., H.P. Crotwell, D.E. McNamara, and G.E. Randall, Regional Wave Propagation in and around the Tibetan Plateau, *Proceedings of the 17th Annual Research Symposium on CTBT Monitoring*, Scottsdale, AZ, September 1995.

Wagner, G.S. and T.J. Owens, Regional wavefield analysis using three-component seismic array data, *Proceedings of the 17th Annual Research Symposium on CTBT Monitoring*, Scottsdale, NY, September, 1995.

Wagner, G.S. and T.J. Owens, Numerical simulations of regional wave propagation in realistic earth models, *Proceedings of the 17th Annual Research Symposium on CTBT Monitoring*, Scottsdale, NY, September, 1995.

## INTERACTIONS/TRANSITION ACTIVITIES

### Meetings and Conferences

Crotwell, H.P., G.E. Randall, T.J. Owens, and D.E. McNamara, Reflectivity modeling of regional Sn propagation within the Tibetan Plateau, *EOS, Trans. Am. Geophys. Un., Fall Meeting Supplement*, F402, 1995.

Owens, T.J. and G. Zandt, Lateral heterogeneities in crustal properties beneath the Tibetan Plateau, *Iris Annual Meeting, Semi-a-moo, WA*, June 1996.

### Transitions with Other Laboratories

This project benefited from good working relationships with the Seismic Monitoring groups at Lawrence Livermore and Los Alamos National Laboratories. The reflectivity code used in Task II was developed by G. Randall under internal USC funding and LLNL funding to USC. We benefit from the work of Howard Patton of LLNL who helped implement the parallel version of the code now in use at USC. In turn, the work under the USC AFOSR contract benefits Steve Taylor and Los Alamos seismic monitoring group by providing detailed analysis of regional propagation in the Tibetan Plateau, which is a key to understanding paths from Lop Nor to India and Pakistan. This exchange of information is expected to continue throughout this project. Former student Dan McNamara continues to work closely with Owens from his position as a LLNL Post-doc.

George Randall left USC for a permanent position at Los Alamos, but continued to be a key advisor for the work of USC Ph.D. student, Philip Crotwell. Crotwell spent about two weeks at Los Alamos in the summer of 1996 and all summer there in 1997. Greg Wagner left USC in September of 1996 and was replaced with Dr. Jeroen Ritsema, formerly of UC-Santa Cruz.

New Discoveries, Inventions, or Patent Disclosures

None.